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Comparison of structural design methods for railway composites and plastic sleepers and bearers

Érica Andrade Silva, Dominik Pokropski, Ruilin You and Sakdirat Kaewunruen

Abstract: Railway sleepers are safety-critical and essential components in a ballasted railway track system. Sleepers could principally be made of different materials, such as, timber, steel, concrete, composite and plastic. The deterioration process of sleepers depends largely on the materials of which they are made. The most popular material for manufacturing sleepers nowadays is concrete. In very recent years, a new type of railway sleeper has been developed using composite and plastic materials. These plastic sleepers have been trialled as bridge transoms and, to a limited extent, as switch and crossing bearers. A limited application of composite (a combination of cement, steel and plastics) to bridge transoms can also be seen. At present, there is no unified design method or standard for these new plastic and composite sleepers and bearers. The lack of design information can compromise public safety. This paper thus highlights the design aspects for plastic and composite sleepers in comparison with traditional materials. It reveals that limit states design concept is the most optimal approach for sleeper design and manufacture. The insight will help rail asset owners and managers establish predictive and condition-based track design and maintenance.

Keywords: sleeper; crosstie; transom; plastic; composite; structural design; railway; track component

1 Introduction

Railway sleepers are significantly important components in ballasted railway track systems (Zhao, Chan, and Burrow 2007). Their main functions are to withstand static and dynamic loads imposed by the wheels and transfer them to the ballast and underlying formation, and to secure the rail gauge to allow trains to travel safely (Kaewunruen and Remennikov 2009). Another important function of the sleepers in a ballasted railway track system is to help provide lateral track resistance to improve the stability and stiffness of the track structure (Kumaran et al., 2003; Koike et al., 2014). Any

83 damage to or poor conditions of sleepers could influence the quality of the railway track, resulting in
84 impaired rail services. For example, if the sleepers cracked severely they would deform highly under
85 the loads imposed by wheel–rail interaction. This large differential settlement accelerates the
86 damage to other railway components, which in turn shortens the maintenance period of the railway
87 track. In addition, if the lateral resistance of the track is insufficient to support lateral forces (i.e.
88 because of loosened ballast or abraded sleepers), rail buckling may occur as shown in Fig. 1
89 (Kumaran et al., 2003).

90 In general, railway sleepers are made of concrete, timber, steel, plastic or a composite
91 material (referred to hereinafter as ‘composite’). Timber, concrete and in some cases steel are
92 traditional materials used to manufacture railway sleepers. Figure 2 gives an actual breakdown (as
93 of 2010) of different types of sleeper used in mainline railway tracks within European countries
94 (UIC 2013). The deterioration process of sleepers depends substantially on the materials of which
95 they are made. Hence, studies have attempted to determine the most suitable material for sleepers
96 with regard to durability, strength and cost (Ticoalu et al., 2008). However, most sleepers
97 deteriorate regardless of their material, thereby reducing their performance capacity. To ensure
98 acceptable track performance, broken sleepers should be replaced by new ones (Manalo et al. 2010).

99 According to Hagaman and McAlphine (1991) and Goldgabr (2009), 14 million timber
100 sleepers are replaced each year by the US railroad industry. McConnell (2008) also states that
101 around 5% of timber sleepers are replaced annually in the US and Canada. In Germany, the railway
102 industry must replace about 11 million timber sleepers in the future (Woidasky, 2008). In Australia,
103 25–35% of the costs of the railway industry are for maintenance, including sleeper replacement
104 (Yun and Ferreira 2003). Therefore, the elevated maintenance costs of sleepers make it even more
105 important to study railway sleeper materials and their design methods.

106 This paper presents a state-of-the-art review of the structural design of railway sleepers made
107 of concrete, steel, timber, plastic or composite, and identifies essential factors such as their life cycle
108 and deterioration process. However, the main focus is on the design concepts of plastic and

109 composite sleepers. Because the use of such sleepers is relatively new in railway industry around the
110 world, this review offers new useful information for the industry. There is a misconception that
111 standard testing procedures (or laboratory type testing for manufacturing quality) could replace a
112 design method. It is therefore important to highlight the necessity of reliable design methods to
113 ensure that future track maintenance does not suffer from the lack of design information so that the
114 service life of the structural and safety-critical component could be determined at a given time in
115 adverse rail environments (Setsobhonkul et al., 2017; Binti Saadin et al., 2017). Commercially,
116 plastic and composite sleepers are often manufactured and fabricated by small and medium-sized
117 enterprises whose product line may not last as long as railway lines do (i.e. the average lifespan of a
118 start-up company is about 5–8 years, whereas a railway line is normally built to last 50+ years).
119 Knowledge of the engineering design principle is therefore crucial for enabling suitable repair,
120 modification and retrofit of the track components in the future (Kaewunruen et al., 2014, 2015,
121 2016). In this paper, we evaluate and explain different design methods associated with plastic and
122 composite sleepers. These insights will help railway engineers determine suitable engineering
123 techniques and solutions for track construction and maintenance under future uncertainties.

124 **2 Different types of sleeper**

125 **2.1 Materials**

126 *2.1.1 Timber*

127 The most common material used to make railway sleepers is hardwood. Nowadays, about 2.5 billion
128 sleepers in railway networks around the world are made of timber. The state of Queensland, in
129 Australia, alone has 8 million timber sleepers in service (Manalo et al. 2010). In China, there are
130 more than 13.8 million timber sleepers under revenue services. Each year, the European wood
131 industry supplies around 390,000 m³ of wooden sleepers, part of which is exported out of Europe.
132 Figure 3 shows the different species of wood purchased in Europe in 2010 (UIC 2013).

133 According to Zarembski (1993), high-quality hardwood timber sleepers perform reliably and
134 capably for many years. However, as they deteriorate, they become less able to meet the

135 performance requirements (Manalo et al. 2010). In the US, the railway industry replaces about 15
136 million timber sleepers each year (Lampo 2002). Such demand makes it necessary to develop an
137 alternative to timber for the railway industry. The main advantage of timber sleepers is their
138 versatility. They are easy to manage, simple to replace, light in weight, high in damping and require
139 no complex equipment. Timber sleepers can also be used in every type of railway track. Therefore,
140 they are attractive to the railway industries of countries in which high-quality hardwoods are
141 accessible.

142 However, one of the main disadvantages of timber sleeper is their susceptibility to
143 mechanical degradation and moisture. The combination of bearing-plate and ballast effects and the
144 fracture of timber sleepers caused by stresses may advance their mechanical failure (Qiao et al.,
145 1998). Because of material degeneration, it is very common for the ends of timber railway sleepers
146 to split (Hibbeler, 2004). Another significant disadvantage of timber sleepers is fungal decay. In
147 Queensland, for example, the most common cause for the failure of timber sleepers is fungal decay
148 (Hagaman and McAlphine 1991). Both main types of failure of timber sleepers are shown in Fig. 4.

149 There are many ways to improve the performance of timber railway sleepers, not least
150 timber preservatives given the high incidence of decay. In addition, dowels can be used to reduce
151 the frequency of splitting (Qiao et al., 1998).

152 *2.1.2 Steel*

153 Because of the scarcity of timber, steel sleepers began to be used in railway networks around the
154 1880s and have advanced since; the original sleeper design has been replaced by the modern Y-
155 shaped one (Ferdous et al., 2015). Australia is among the countries with the most steel railway
156 sleepers, with 13% of its stock made of steel nowadays (Manalo et al., 2010). However, compared
157 to timber sleepers, more care is required during the installation and tamping of steel sleepers
158 because their inverted shape complicates the ballast-packing process. This aspect makes steel
159 sleepers more expensive to manufacture and to maintain.

160 According to several studies, there are many reasons why steel sleepers are not the preferred
161 choice in railways networks. The main ones are their high corrosion rates, difficult ballast contact
162 and appreciable electrical conductivity (Ferdous and Manalo 2014). They corrode because of salts in
163 the ballast, soil and groundwater, as can be seen in Fig. 5. Given that steel sleepers are prone to
164 corrosion, it is essential avoid bringing them into contact with salt-bearing materials (ETC-02-03
165 2009). Another problem with steel sleepers is fatigue cracking due to repeatedly imposed loads
166 (Ferdous and Manalo 2014). These problems with corrosion and fatigue cracking mean that steel
167 sleepers are not always the appropriate choice. In addition, according to Manalo et al. (2010),
168 handling and installation are more difficult with steel sleepers, which also increase the maintenance
169 costs.

170

171 2.1.3 Concrete

172 Nowadays, in railway networks around the world, about 500 million concrete sleepers are required
173 every year, which is more than half the total demand. Concrete is the principal material used for
174 sleepers in many countries around the world. The increasing use of concrete sleepers is due to the
175 need of the railway industry to replace aging timber by more durable concrete (Ferdous et al., 2015).

176 Concrete sleepers present damage similar to that in concrete structures because they use the
177 same material. Depending on the consequences to the sleepers, this damage can be classified into
178 different types. One common type in concrete sleepers is longitudinal cracks (see Fig. 6), which
179 usually start at the dowels and continue along the sleeper, even before loading occurs. The main
180 causes of such cracks are incorrect placement of the dowel screws, the presence of sand in the
181 dowels and dowels that rupture because of the expansion of frozen water (Rezaie, 2012a. 2016b).

182 In Australia, the first concrete sleepers were used in 1970, and currently mono-block
183 prestressed concrete is the material of choice (Kaewunruen, 2010). Because concrete sleepers are
184 effectively prestressed concrete beams, the pre-stressing force is one of the most important
185 parameters to be considered in the structural design process. However, even if the tensile strength of

186 concrete is low, longitudinal cracks may occur before traffic loading occurs. This is due to the high
187 pre-stressing force that is applied to the concrete. Therefore, the tensile strength and pre-stressing
188 force are the two most important parameters that determine the occurrence and propagation of
189 longitudinal cracks (Rezaie et al., 2016). The negative point of using this type of sleeper is the high
190 cost involved (Rezaie et al., 2016).

191

192 2.1.4 *Plastic and composite*

193 Plastic sleepers are now being used more by the railway industry, with composite also being useful
194 in sleeper manufacturing. Different papers have different meanings for composite and plastic
195 sleepers. In this paper, we consider plastic sleepers as being those made of recycled plastic or
196 vehicle tyres (or something similar), with no (or barely any) fibre reinforcement. Meanwhile, we
197 consider composite sleepers as being either those made of long-fibre composites or whose strength
198 has been increased by adding long-fibre composites to the original ones.

199 Recent studies have been conducted globally to develop technologies for composite and
200 plastic sleepers. These developments are aimed at reducing the number of timber sleepers in railway
201 networks. Such composites try to imitate the behaviour and performance of timber while reducing
202 maintenance costs and minimizing environmental impact (Ferdous et al. 2015).

203 Recycled rubber is added to some types of plastic sleeper. According to (Pattamaprom et al.
204 2005), natural rubber has better hardness and compressive modulus compared to other materials.
205 However, engineered rubber has greater stiffness and inelasticity. Japan has recently developed
206 synthetic sleepers made of glass fibre and hard polyurethane foam. This type of composite sleeper is
207 designed to have a long lifespan and the same physical properties as timber ones. These synthetic
208 sleepers have also been used in places where replacement is more difficult, for example in switches
209 and girder bridges (Miura et al. 1998). Figure 7 shows an example of composite sleepers.

210 Another possibility is to use fibre composites to increase the strength of original sleepers
211 (Manalo et al. 2010). Qiao et al. (1998) showed that the performance of timber sleepers improved

212 appreciably when they were enveloped in grass-fibre-reinforced polymer (GFRP). These GFRP–
213 timber sleepers were stiffer and could support greater imposed loads compared to the original
214 timber sleepers. The treatment also reduced stresses and increased the surface resistance to ballast
215 attrition. In addition, grass fibre improves the durability of timber sleepers (TTCI. 2005)..

216

217

218 **2.2 *Topological design aspects***

219 Each sleeper has its own characteristic size, shape and dimensions according to its material, the type
220 of railway in which it is used and the company that operates the railway. General design aspects are
221 described in Table 1 for each sleeper material. Several aspects should be considered when
222 determining the shape, size and dimensions of a sleeper. For example, the length of a sleeper
223 depends on the track gauge. The choice of material is also an important factor when determining
224 these design aspects because it will dictate the time and costs of manufacturing and maintenance, as
225 well as the deterioration process.

226

227 **3 Design aspects**

228 **3.1 *Life cycle and deterioration process of sleepers***

229 The life cycle of a sleeper depends directly on the material of which it is made and on the quality of
230 that material. Other factors such as imposed load, temperature change and chemical elements
231 present in the atmosphere also affect sleeper life cycle. The main causes of failure of each type of
232 sleeper are listed in Table 2.

233

234 **3.1.1 *Timber sleepers***

235 One of the most important issues with regard to timber sleepers is rotting. Wetting environments
236 facilitate the biological degradation of timber sleepers by fungus because timber is an organic
237 material. This issue is referred to in general as fungal decay (Ferdous and Manalo 2014). Another

238 common problem with timber sleepers is end spitting, which is caused by the behaviour of the
239 timber itself (Manalo et al. 2010). These two issues are the main reasons why timber sleepers fail
240 (Ticoalu et al. 2008). Insect attack (e.g. from termites) is another common problem for timber
241 sleepers (Ferdous et al. 2014a, 2015b).

242

243 3.1.2 *Steel sleepers*

244 The life cycle of steel sleepers is determined by the build-up of fatigue over time (ETC-02-03 2009).
245 Fatigue cracking occurs because of train-induced movement in the fastening holes (Manalo et al.
246 2010). The rail-seat area is exposed to fatigue failure due to the repeated imposition of excessive
247 loads on the rails (ETC-02-03, 2009; Ferdous and Manalo 2014). Steel sleepers are also susceptible
248 to chemical harm and corrosion, mainly when they come into contact with salts in the ballast and
249 other subgrade materials (ETC-02-03 2009; Ferdous and Manalo 2014).

250

251 3.1.3 *Concrete sleepers*

252 Rail-seat damage is the most serious cause of failure in concrete sleepers around the world. This
253 issue can be caused by several factors, but rail-seat abrasion is the most harmful one (Ferdous and
254 Manalo 2014). According to Kaewunruen and Remennikov (2009), cracks are common in concrete
255 sleepers because of the inconstant and considerable loads due to irregular wheel imperfections.

256 Some problems associated with concrete sleepers are similar to those with other concrete
257 structures, such as sulphate attack, alkali–aggregate reaction and acid attack. Sulphate salts are
258 present in the soil, groundwater and aggregates, and may react with hydrated cement past to produce
259 expansive products that cause the sleeper to crack (Neville 2011). According to (Shayan and Quick
260 1992), the alkali–aggregate reaction is responsible for longitudinal cracking parallel to the top of the
261 sleeper and map cracking in its ends. Acid attack is common in concrete given that the constituent
262 cement is not resistant to it and is consequently destroyed (Ferdous and Manalo 2014).

263

264 3.1.4 *Plastic and composite sleepers*

265 The process of manufacturing plastic and composite sleepers creates voids inside the materials that
266 concentrate any applied load. This process is responsible for failures before the design lifetime
267 (Ferdous et al. 2015). Another important issue with plastic and composite sleepers is the loosening
268 of the fastening system caused by creep deformation, the extent of which depends on the magnitude
269 and frequency of the applied loads (Nosker1998; Ferdous et al. 2015). Fatigue cracking is a serious
270 problem in plastic and composite sleepers because they are made of heterogeneous and anisotropic
271 material.

272 Plastic sleepers can fail through fibre fissure, delamination, matrix fracture and fibre–matrix
273 de-bonding (Degrieck and Paepegem 2001). Elevated temperature can also alter the performance of
274 plastic sleepers, which expand if the temperature changes are excessive (Ferdous et al. 2015).
275 Another disadvantage of plastic sleepers is material disintegration. Figure 8 shows an example of
276 the failure of each type of sleeper.

277

278 3.2 *Environmental effects*

279 Environmental effects are important when choosing a sleeper material. The main environmental
280 effects associated with each type of sleeper material are detailed in Table 3 in relation to
281 manufacturing and maintenance.

282

283 3.3 *Focus on plastic and composite sleepers*

284 This paper highlights the disadvantages of the timber, concrete and steel sleepers that have been
285 used by the rail industry throughout the years. Concrete and steel sleepers have now largely replaced
286 the original timber ones, but concrete and steel themselves are not without their problems;
287 sometimes it is actually better to replace old timber sleepers with new ones (Ferdous and Manalo
288 2014). Table 4 lists the properties of the various sleeper materials. The performance of plastic and

289 composite sleepers is summarised in Table 5 (Ferdous et al. 2015; Kaewunruen and Remennikov,
290 2016; Kimani and Kaewunruen, 2017).

291 Recent studies around the world have looked for alternative materials in which the cited
292 problems are less common and with which the maintenance costs should be reduced: plastics and
293 composites are seen as such alternative materials. They do not corrode easily, are resistant to insect
294 attack, and have high electrical resistance and low thermal conductivity (Ferdous et al. 2015).
295 According to Lampo (2002), the manufacturing of recycled plastic sleepers is associated with a
296 remarkable reduction in greenhouse gases. Furthermore, plastic sleepers can be manufactured in
297 several different ways, which make railway industry hesitate to adopt a single method for design or
298 type testing.

299 The number of companies investing in these recent technologies is increasing considerably
300 (Manalo et al. 2010). Because of the recent growth in the use of plastic sleepers, research is required
301 to assess their behaviour, limitations and environmental effects. The present review analyses the
302 common design methods used for sleepers, with the aim of evaluating the reliability of composite
303 and plastic sleepers.

304

305 **4 Design concept for plastic sleepers**

306 ***4.1 Design challenges***

307 Because plastic is not an isotropic material, a specific drawback of plastic sleepers is that they have
308 different strength in different directions. It is easier to design in concrete or steel because these
309 materials have constant strength in all directions. Although timber is also an anisotropic material, it
310 has been used in civil engineering for long time and designers are familiar with its behaviour. As
311 yet, we do not have enough experience of using plastic in railway applications, and difficulties with
312 designing plastic sleepers are intensified by their anisotropy, fragility, low tensile strength, light
313 weight and the dependence of the properties of their topology. These issues increase the design

314 complexity of composite and plastic sleepers; the design process must consider the sleeper material
315 as well as its form and size (Awad et al. 2012).

316 Several standards and specifications cover the design of timber, steel and concrete sleepers
317 because of their ubiquity. Timber sleepers are covered by RailCorp SPC 231 and AS 3818.2, steel
318 ones by Australian Rail Track Corporation (ARTC) ETA-02-03 and AS 1085.17, and concrete ones
319 by AS 1085.14 and RailCorp SPC 232. However, there is no specific design code for plastic
320 sleepers, although the American Railway Engineering and Maintenance-of-Way Association
321 (AREMA), the Chicago Transit Authority and the Union Pacific Railroad provide some
322 specifications for their design (Ferdous et al. 2015). The absence of a consistent standard has
323 resulted in non-uniformity in the manufacturing of plastic sleepers, which in turn creates uncertainty
324 over using this material in long-term operation.

325 Most designs of composite and plastic sleepers are based on associated specific research
326 outcome and guidelines. Experimental tests performed to benchmark structural capacity and
327 manufacturing quality (i.e. type testing) using a certain number of sleepers and re-analysis are often
328 chosen depending on the designer's experience and the risk management plan taken by the railway
329 organisation (though increased inspection and maintenance). For composite sleepers and bearers,
330 any design method should consider the fibre layers, all dimensional aspects and structural functions
331 of the sleepers and bearers (Kaewunruen, 2014a-c; Kaewunruen et al., 2017). Consequently,
332 designers should use optimization methods after the experimental tests to seek an ideal solution in
333 both aspects (Awad et al. 2012).

334 Numerical simulation is often used in the design of concrete, steel and timber sleepers, an
335 example of which is shown in Fig. 9. Such numerical methods may be used to design composite and
336 plastic structures as well, but the design process in that case is complicated by the uncertainty and
337 variation in material quality, which depends on the process used to manufacture the composite or
338 plastic sleepers. In contrast, it takes a long time to test several sleepers experimentally and requires

339 the use of appropriate facilities. This difficulty also discourages the sufficient number of repeated
340 tests since it increases the costs (Awad et al. 2012).

341

342 **4.2 *Design principles***

343 **4.2.1 *Allowable-stress design***

344 Allowable-stress design (also known as permissible-stress design) is a design concept used
345 commonly to design traditional sleepers. Allowable-stress design is more conservative than limit
346 states design because the former considers only quasi-static wheel loads (Kaewunruen et al. 2014),
347 which need higher safety factors making the design method unsatisfactory. A quasi-static wheel
348 load is usually multiplied by a dynamic factor of between 2.0 and 3.0 (AS1085.14 2003), (AREMA
349 2006). However, wheel–rail interactions can produce dynamic loads higher than those specified in
350 the design codes. A recent studied showed that dynamic wheel loads can reach four to six times the
351 static ones (Leong and Murray 2008). Figure 10 shows the static wheel loads that are considered in
352 allowable-stress design.

353 The allowable-stress design concept is present in the concrete sleeper design standards used
354 in Australia, Asia and North America. However, because this approach has to consider reductions in
355 material strength, the resulting sleepers are over-designed (Kaewunruen, Remennikov, and Murray
356 2014), which is a concern for railway companies. Also, it omits the important factors in sleeper
357 design, such as real dynamic load, ultimate material strength and risks associated with operation,
358 maintenance and even failure (Kaewunruen et al. 2014). These are the main disadvantages of using
359 this design principle.

360 As shown in Fig. 11, this design concept determines the maximum strength of some
361 material, which then cannot be exceeded in the structure. Aspects such as buckling, brittle fracture,
362 fatigue failure and allowable deflections are taken into account in this design method. In this
363 concept, the limit strength of the material is reduced by factors associated with errors in material
364 homogeneity, size and finishing (Mrema 2011) Examples of some reduced factor values are given in

365 Table 6 for each type of sleeper. The highest factor is for timber sleepers because timber is the least
366 homogeneous of the materials.

367

368 4.2.2 Limit states design

369 Recently, limit states design has been used for concrete sleepers in Europe and South Australia. This
370 concept takes into account the ultimate strength of materials by extensive analysis and
371 experimentation, as shown in Fig. 12. Over the past 7–8 years, limit states design has replaced
372 allowable-stress design because the former has many advantages such as less material waste and the
373 implementation of new material technologies (Remennikov et al. 2012). These factors make limit
374 states design superior to allowable-stress design because the former leads to much more optimal
375 sleeper manufacturing.

376 Limit states design calculates the strength of a structure by multiplying its resistance by
377 reduced factors (ϕ), which should be superior to multiplying the imposed loads by load factors (γ)
378 (Remennikov et al. 2012). Therefore,

$$379 \quad \Sigma (\gamma \times \text{imposed loads}) \leq (\phi \times \text{resistance}) \quad (1)$$

380 or

$$381 \quad \text{Design effects} \leq \text{Design capacity}, \quad (2)$$

382 where the design effects taken into account are the shear forces, bending moments and axial forces
383 imposed on the sleepers. These can be static or dynamic, depending on the analysis method
384 (Remennikov et al. 2012).

385 This concept is based on a deterministic model. However, the resistance and loads factors
386 are based on a probabilistic model, which means a reliable statistical distribution of loads and
387 resistance (Kaewunruen et al. 2012). Figure 13 shows an example of a statistical probability
388 distribution. Failure will happen in the area of the curves in Fig. 13 in which the distribution of load
389 effects reaches that of the capacity. In limit states design codes, the probability of failure relates p_f to
390 the reliability index or safety index β through

$$\Phi(-\beta) = p_t \quad (3)$$

where the factor Φ is a cumulative distribution curve (AS5104 2005) Figure 14 shows how the safety factors and probability of failure are related. The limit state can be divided into the following limit states.

The ultimate limit state is associated with one event that can cause a sleeper to fail because of the imposed loads. The analysis is probabilistic, which means it is based on the results of experiments involving loading over a period of time (usually more than one year); a statistical analysis takes into account the importance of the train and operational data (Ferdous et al 2015). Failure is common at the midspan and the rail seat. This limit state is more common in concrete sleeper design (Kaewunruen 2007).

The fatigue (damageability) limit state considers the accumulated damage caused by the loads over a long period of time. Therefore, the sleeper lifetime is determined by the design service time to support repeated loads; the design service time should be longer than the actual life of the sleeper (Kaewunruen et al. 2014).

Finally, the serviceability limit state is the limit state that defines when problems incur during revenue services (such as displacement, ride quality, gauge and rail cant, etc.). Failure of a significant number of sleepers may reduce its operational capacity. Currently, this limit state is used in the replacement of sleepers made of different materials based on track stiffness (Kaewunruen et al. 2014).

4.3 Application of design principles to plastic and composite sleepers

4.3.1 General design aspects

Currently, the design of composite and plastic sleepers is based on allowable-stress design. To guarantee better reliability, static and dynamic loads should be considered in the design (Ferdous et al 2015). According to (Remennikov, Kaewunruen 2007), a quasi-static wheel load is about 1.4–1.6 times a static one, when the track is well maintained to a very good condition. Because this concept

417 does not take dynamic loads into account, the load factor used is usually taken as 1.5 times of rail-
418 seat loads. However, calculation of the real dynamic loads is important to guarantee better analysis
419 of sleeper performance, rather than merely some estimates. Therefore, the effects of real dynamic
420 loads should be considered and included in sleeper design standards to increase the design reliability
421 (Ferdous et al 2015).

422 In addition, the design of fibre composite sleepers is usually based on the allowable
423 deflection limit (Awad et al. 2012). The serviceability deflection limit permitted by the
424 EUROCOMP design code is between $L/150$ and $L/400$ for composites structures, where L is the
425 span (Clarke 1996). In the absence of standards for fibre composite structures, civil engineers use
426 various methods to design these structures, such as optimization and finite-element analysis (FEA).
427 Both methods can be used to design these structures according to their serviceability limits (Awad et
428 al. 2012).

429 In the design of fibre composite sleepers, FEA is important for determining in which areas
430 the stresses are higher, and consequently where the fibres should be placed. This is an intuitive and
431 iterative method that can also determine in which areas the stresses are lower and so material can be
432 removed. This addition and removal of polymers and fibres should happen until the sleepers have
433 the strength required by the serviceability conditions and the costs are the lowest possible (Ferdous
434 et al 2015). By optimizing the material distribution, this method is very useful for designing
435 composite sleepers. It avoids material waste by reducing the height and weight of the sleepers,
436 thereby reducing manufacturing costs appreciably.

437 Another way to design fibre-reinforced polymer composite sleepers is via optimization.
438 Awad et al. (2012) demonstrated several different optimization methods, such as design sensitivity
439 analysis, genetic algorithms and simulating annealing. However, the method most used is the finite-
440 element method, which can be applied to various composite structures (Prochazka, Dolezel., and
441 Lok 2009). All these methods have the same objective: to optimize the sleeper design, thereby
442 reducing material waste and manufacturing costs, among others.

443 Despite the absence of design standards for composite sleepers, AREMA (2006) currently
444 require plastic sleepers to satisfy minimum criteria for mechanical and physical performance. In
445 addition, the Japanese code JIS 2101 (Takai et al., 2006) and Koller (2015) also specify certain
446 properties required of FFU (fibre-reinforced formed polyurethane). However, these design codes are
447 currently limited in practice, and the behaviour of composite sleepers requires further research
448 (Ferdous et al 2015; Kaewunruen, 2014b). The lack of standards limits the ability to retrofit or
449 maintain such sleepers during the service life.

450

451 4.3.2 *Comparison and application of methods*

452 The design of prestressed concrete sleepers is usually done by allowable-stress design, which is the
453 preferred approach in standards such as AS 1085.14 (2003). However, allowable-stress design is
454 more conservative than limit states design. Therefore, using allowable-state design, the
455 effectiveness of the sleepers is reduced and their cost is increased (Kaewunruen 2007). The same
456 happens with the design of composite sleepers, so limit states design should be researched further
457 for composite and plastic sleepers to guarantee acceptable values for the reduction factors and
458 partial-load factors (Ferdous et al 2015) and to further optimize the design. A comparison between
459 the allowable-stress and limit states design methods is given in Table 7.

460 There are several companies around the world that are producing different types of plastic
461 and composite sleepers, each of which uses a different methodology to design its own products;
462 some companies known to be active in the railway field are listed in Table 8. Allowable-stress
463 design is preferred in different parts of the world for designing plastic sleepers. However, the
464 absence of a consolidated standard has spawned several different sets of guidelines for designing
465 plastic and composite sleepers.

466 As mentioned before, allowable-stress design is a conservative approach that usually results
467 in over-designed sleepers. The performance benchmarking is in fact based on timber and its
468 performance, but it is found that not all behaviours are mapped. The reduced factors consider only

469 40–50% of the real material strength, which shows how moderate this method is. Many researchers
470 around the world are working on the limit states design method for railway sleepers, trying to reduce
471 the amount of material used and consequently the manufacturing costs.

472 Van and McKay (2013) state that transoms (large sleepers used on railway bridges) have
473 higher strength requirements than those of commonly used sleepers because the latter are supported
474 by ballast. The design requirements for common transoms are given in Table 9; the method used to
475 design these transoms is once again allowable-stress design. According to Table 6, the maximum
476 bending moment required is 60 kN m, which corresponds to roughly half the real bending moment.
477 Therefore, the value of the reduced factor is 0.5, which is a typical value for plastic sleepers. This is
478 a real example of how allowable-stress design works for transoms.

479 The CarbonLoc company has promoted a new technology of a hybrid plastic transom with
480 steel bars inside a plastic sleeper. In 2007, the ARTC used several of these transoms on a railway
481 bridge in Hunter Valley, Australia (Van Erp and McKay 2013), some of which are shown in Fig. 15.

482 As mentioned before, the reduction of 40–50% in the material strength makes allowable-
483 stress design inappropriate for designing plastic sleepers because this reduction does not consider
484 plastic behaviour such as fatigue or dynamic dumping. This method merely reduces the total
485 strength of the material without a complex analysis of the real behaviour of plastic and composite
486 sleepers.

487 The fact that there are few available standards to guide the design of composite and plastic
488 sleepers restricts their use and application in railways networks (Ferdous et al. 2015; Kaewunruen,
489 2015). To increase the number of composite sleepers used, further research should be undertaken to
490 guarantee better knowledge about these sleepers.

491

492 **5 Conclusions**

493 The use of plastic and composite sleepers and bearers has increased by degrees in rail networks
494 around the world, but their structural design is yet to be thoroughly determined. The disadvantages

495 of timber, concrete and steel sleepers have inspired research into this new technology of plastic and
496 composite sleepers. These could be made of recycled plastic so that less carbon dioxide is emitted
497 into the atmosphere. These materials have many suitable properties, such as durability, lightness and
498 high damping. However, some disadvantages of plastic sleepers are their low stiffness, low strength,
499 light weight (for track stability) and high plastic deformations due to elevated temperatures.

500 At present, there are only several guidelines that are used inconsistently to design and
501 manufacture plastic and composite sleepers/bearers. It is important to note that there are no specific
502 structural standard or method for the design of plastic and composite sleepers/bearers. This could
503 lead to serious safety risks over their service life. This review has highlighted the necessity for
504 further research into the design of plastic and composite sleepers/bearers to ascertain public safety
505 and operational reliability over time.

506 Based on the comparison of structural design methods for railway composites and plastic
507 sleepers, it could be found that allowable-stress design is a conservative approach. The information
508 about material-strength reduction of composites and plastics does not justify the use of such a
509 design principle. That is why more research should be undertaken to underpin the reliability and
510 safety of the process of designing such sleepers. This state-of-the-art review has also revealed that
511 different design guidelines use different values of reduced-strength factors in the allowable-stress
512 design method. Thus, railway authorities should pay special attention to the use of plastic and
513 composite sleepers and ensure that high-quality track maintenance is always planned as required
514 during the service life of the sleepers. In addition, it was found that limit states design takes into
515 account the ultimate strength of the material and other important failure-mode and serviceability
516 considerations. This makes that approach more suitable than allowable-stress design for plastic and
517 composite sleepers' design and manufacture. Since, the field experience of composites and plastics
518 sleepers are rather limited, it is recommended that future work be focussed on the unified limit
519 states design method of plastic and composite sleepers and bearers in order to ensure the railway's
520 safety, stability and durability.

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700 **Table 1 .** Topological design aspects for each type of sleepers

Material	Outside design aspects	Images
Timber	The timber sleepers are usually rectangular due the difficulty of designing different shapes in timber bodies. The Australian Standard (ARTC) recommends the following dimensions with their correspondent tolerances: length (standard gauge) = 2440+75mm; length (broad and mixes gauge) = 2600+50mm; width = 230+25mm and depth = 130+10mm.	 (Rail News 2015)
Steel	Recent railways have used 'Y-steel-sleepers' instead the orthogonal steel ones (Hibbeler.2004). These modern sleepers have more resistance to support cross movements due to the ballast between the parts of the 'Y'. However, these 'Y-shape' are indicated to areas with reduced radius because the contact area is limited (Rail News 2015).	 (Manalo et al.2010)
Concrete	Several concrete sleepers have a complex shape because concrete is easily workable. Hernandez, Koch, and Barrera (2007) shows, for example, the dimensions of the used concrete sleepers. However, the University of Queensland design a rectangular pre-stressed concrete sleeper appropriate to replace timber ones (EFRTC 2007) .	 (Allbiz)
Plastic and Composite	Fibre composites sleepers may be manufactured with similar dimensions to timber ones (Ticoalu, Aravinthan, and Karunasena 2008). However, the shape, size and dimensions of polymer sleepers depend on the company which produce them and the type of plastic used (Ferdous et al 2015).	 (Lankhorst)

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702 **Table 2.** Life cycle and failure causes of each type of sleepers

Material	Life Cycle	Failure Causes
Timber	* Hardwood – 20-30 years * Softwood – 20 years (Manalo et al.2010)	<ul style="list-style-type: none"> ▪ Fungal decay ▪ End splitting ▪ Insect attack
Steel	50 years (Manalo et al.2010)	<ul style="list-style-type: none"> ▪ Fatigue cracking ▪ Corrosion
Concrete	50-60 years (SPC 232 2012)	<ul style="list-style-type: none"> ▪ Rail-seat corrosion ▪ High impact loading ▪ Sulphate attack ▪ Alkali-aggregate reaction ▪ Acid attack
Plastic and Composite	50 for fibre-reinforced Foamed Urethane (Manalo et al.2010),and 60 or more for glass fibre-reinforced hard polyethylene foam (Ferdous, Manalo 2014)	<ul style="list-style-type: none"> ▪ Voids ▪ Wear & tear ▪ Decomposition ▪ Permanent deformations ▪ Fatigue cracking ▪ Elevated temperature

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Table 3. Environmental effects of material used in sleepers

Material	Environmental effects
Timber	<ul style="list-style-type: none"> A considerable amount of tree are cut to timber sleepers manufacturing (Ferdous et al 2015). The emission of carbon dioxide during operation. The use of chemical substances to reduce the decay rate may affect expressively the environment (Thierfelder, Sandström 2008).
Steel	<ul style="list-style-type: none"> The steel industry produces a large amount of carbon dioxide during its production (Ferdous et al 2015). However, during the operation, the emission is insignificant. The high corrosion rates reduce the time for replacement, which generate more waste.
Concrete	<ul style="list-style-type: none"> The concrete industry also produces a large amount of carbon dioxide during its production (Ferdous et al 2015), and the emission is reduced significantly in operation period. The high replacement rate due sulphate and acid attack, and alkali-aggregate reaction. The concrete wasted during the production.
Plastic and Composites	<ul style="list-style-type: none"> Plastic is not a bio-degradable material, and, if not recycled, it will be discharged in the environment unsustainably. The plastic, which is not recycled, is made of petroleum which makes it unsustainable. Therefore, recycled plastics are the preferable ones.

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Table 4. Summary of properties of different materials sleepers (Manalo et al.2010)

Properties	Hardwood	Softwood	Concrete	Steel	Plastic/composite
Adaptability	Easy	Difficult	Difficult	Difficult	Easy
Workability	Easy	Easy	Difficult	Difficult	Difficult
Handling and installation	Easy	Easy	Difficult	Difficult	Easy
Durability	Low	Low	High	Low	High
Maintenance	High	High	Low	High	Low
Replacement	Easy	Easy	Difficult	Difficult	Easy
Availability	Low	High	High	High	Low
Cost	High	Low	Very high	Very high	Low
Fasteners	Good	Poor	Very good	Poor	Good
Tie ballast interaction	Very good	Good	Very good	Poor	Good
Electric conductivity	Low	Low	High	Very high	Low
Impact	High	High	Low	Medium	Low
Weight (kg)	60-70	60-70	285	70-80	45-75
Service life (years)	20-30	20	60	50	60

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712 **Table 5 Comparison of the performance of composite sleeper** (Ferdous et al 2015)

Types of sleeper Properties	Timber	FFU	TieTek	Axion	InegriCo	Wood core	Glue laminated
Density, (kg/m ³)	1085	670-820	1153	849-897	1121	993	-
Modulus of Elasticity, (MPa)	16000	8100	> 1724	1724	1655	1517	5190
Modulus of Rupture, (MPa)	65	142	> 18.6	20.6	18.6	17.2	103
Compressive MOE, (MPa)	-	-	269	176.5	262	241	-
Rail-Seat Compression, (MPa)	60	58	16.5	20.6	15.9	15.2	-
Screw Pullout Force, (kN)	40	65	35.6	31.6	73.4	-	63.8
Thermal Expansion, (cm/cm/°C)	-	-	1.35×10 ⁻⁴	0.74×10 ⁻⁴	1.26×10 ⁻⁴	0.2×10 ⁻⁴	-
Electrical Impedance (wet), (Ω)	-	140×10 ⁶	500×10 ⁶	-	-	-	-
Flammability	-	-	No@20s	-	-	-	-
Impact bending strength, (MPa)	-	41	-	-	-	-	-

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Table 6 Reduced factors values in allowable stress design


Members	Reduced factor	Source
Prestressed concrete sleeper – at operational performance level	0.50	AS 1085.14719
Prestressed concrete sleeper – at fully operational performance level	0.45	AS 1085.14720
Steel sleeper	0.40-0.60	AS 1085.14722
Timber sleeper – permissible tension stress	0.60	BS 5268
Composites sleeper – at service at top and bottom of centre of sleeper, and at top of rail seat	0.40	Rajendran and Tensing (Rajendran, and Tensing 2015)

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Table 7 Comparison of allowable stress design method and limit state design method (You, R., Silva 2017)

Items	Allowable stress design	Limit state design
Basic principle	working stress ≤ permissible stress ≈ ultimate stress/SF	Σ (γ x imposed loads) ≤ (φ x resistance)
Filled status	Excess the permissible stress	Divide into ultimate limit state serviceability limit state etc.
Load	Use dynamic factor	Combine the loads that multiplied by a load factor
Material strength	Ultimate stress/SF	Based on the degree of reliability
Reliability index	Not take into account	Use reliability index or safety index
Structure importance factor	Not take into account	Depend on the category
Common sleeper material	Concrete, timber, steel, plastics, composite	Concrete, steel

Name	Material	Country	Design Method	Source	Images
AXION	100% recycled plastics	USA	AREMA	Railway-technology	
TieTek	85% recycled materials (plastic, rubber, fiberglass)	USA	AREMA	TieTek web-site	
IntegriCo	Landfill-bound recycled plastics	USA	AREMA	IntegriCo web-site	
Wood core	Plastic mixture reinforced by wooden beam	USA	AREMA	Southwest RV and Marina	
I-plas	100% recycled plastic	UK	Network Rail	Greener Business	
Ecotrax	High density polyethylene and polypropylene plastic recycled.	New Zealand	AREMA and ASTM	SICUT	
KLP	100% recycled plastics	Netherlands	French national railroad company SNCF	Lankhorst	
MPW	Mixed Plastic wastes and glass fibre waste	Germany	WO 9808896 A1 (UPS), WO 2000044828 A1 (Polywood), US 639 1456 B1, among others	Fraunhofer ICT (2010)	
FFU	Fibre-reinforced Foamed Urethane	Japan	JIS E1203	SEKISUI web-site	

		China	CJ/T 399	Xssunrui web-site	
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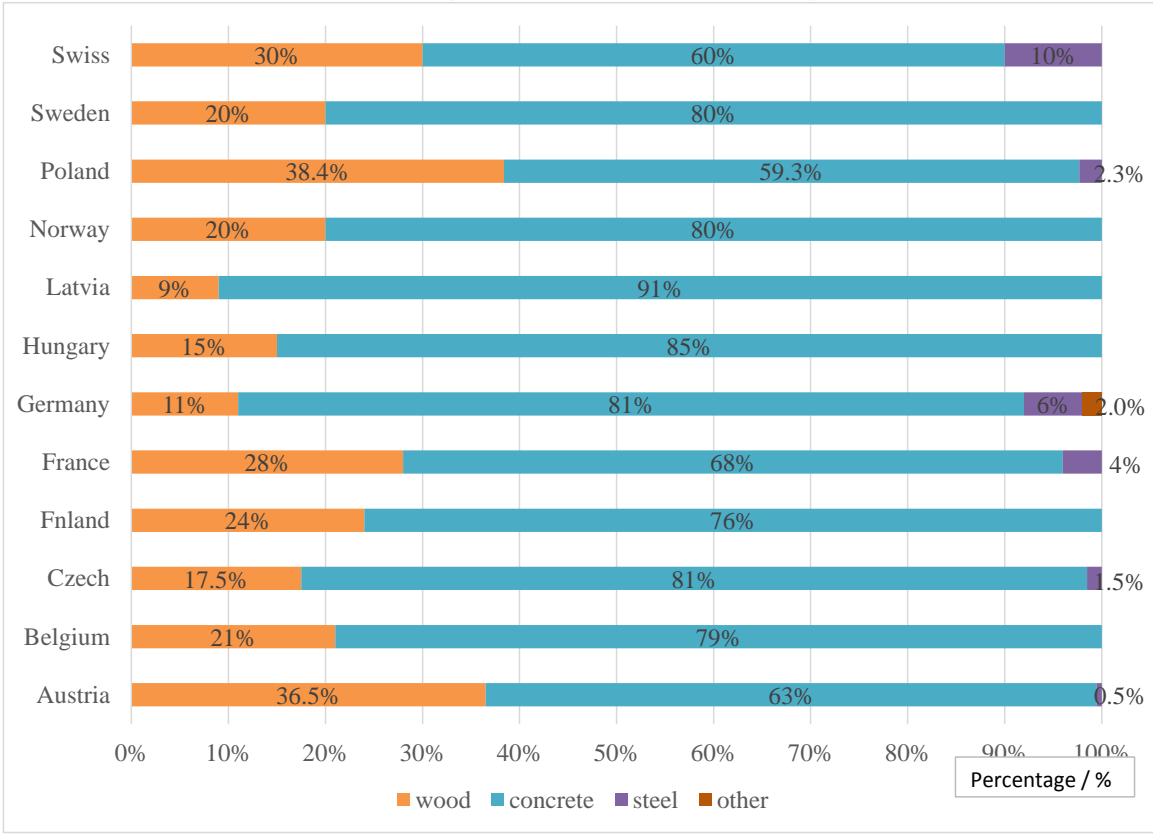
729 **Table 9** Requirements for a typical transom (Kaewunruen 2008a, 2014b, 2017c; Wu 2017)

Limit State Action Effect	Axle Load (tonne)	Distance rail to girder web	Limit State Design Requirement
Strength Limit State Bending Moment	30	250 mm	60 kNm
Strength Limit State Shear Force	30	n/a	200 kN
Fatigue Limit State Bending Moment	30	250 mm	18.75 kNm
Fatigue Limit State Shear Force	30	n/a	75 kN

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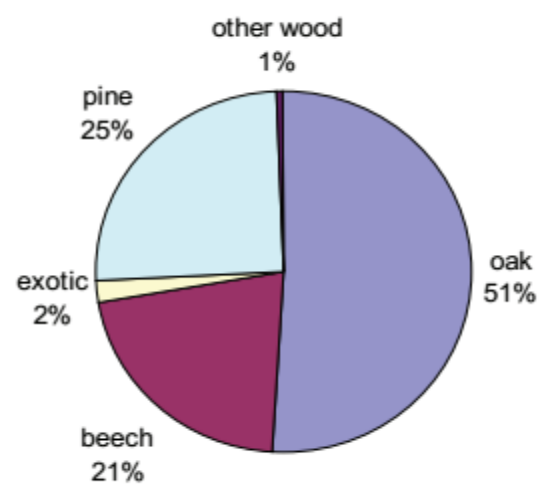


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746 **Figure 1.** Rail buckling due to lateral movements of sleepers, commonly found in timber and steel sleepered tracks
747 (Kumaran, Devdasand Krishnan 2003)



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749 **Figure 2.** Different kinds of sleepers used in main tracks of European countries (UIC 2013)

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Figure 3. The different species of wood purchased in Europe, in 2010 (UIC 2013)



(a)



(b)

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Figure 4. Types of timber sleeper failure. (a) Fungal degradation, (b) end splitting (Manalo et al.2010)



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Figure 5. Corrosion in steel sleepers due salt deposits (Hernandez, Koch, and Barrera 2007)



Figure 6. Longitudinal cracks in concrete sleepers (Rezaie, Bayat, and Farnam 2016)



Figure 7. Composite sleepers in Zollant Bridge, Austria (SEKISUI)



(a)



(b)



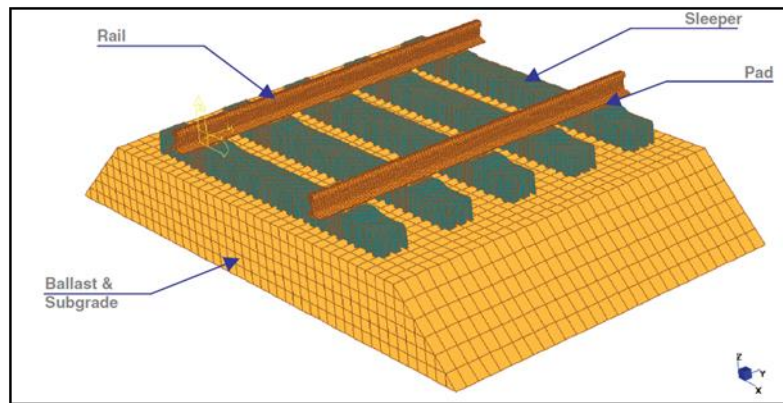
(c)



(d)

Figure 8. Failures of each type of sleepers a) Timber sleepers: end splitting, b) Steel sleepers: corrosion, c) Concrete sleepers: rail-seat abrasion, d) Plastic sleepers: cracking at fasteners (Hernandez 2007; Ferdous 2014a,2015b)

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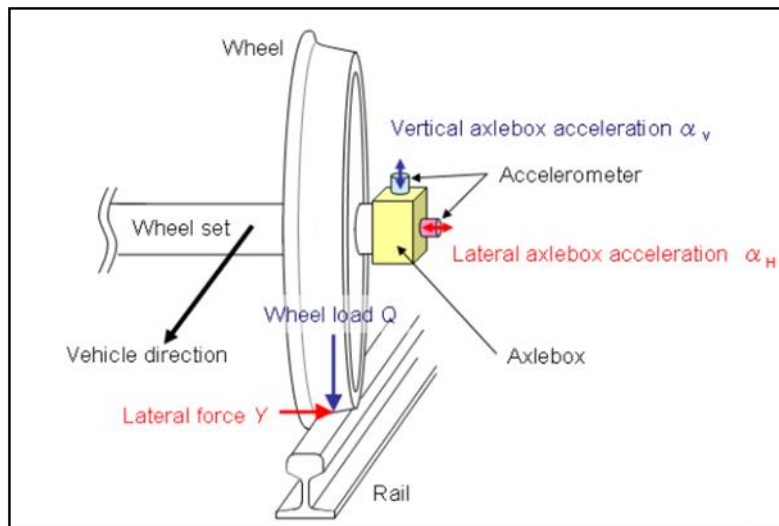
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Figure 9 Components of railway tracks in a numerical simulation (Kaewunruen, Remennikov, and Murray 2014)



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Figure 10. Static wheel loads (Tanaka, Furukawa 2008)

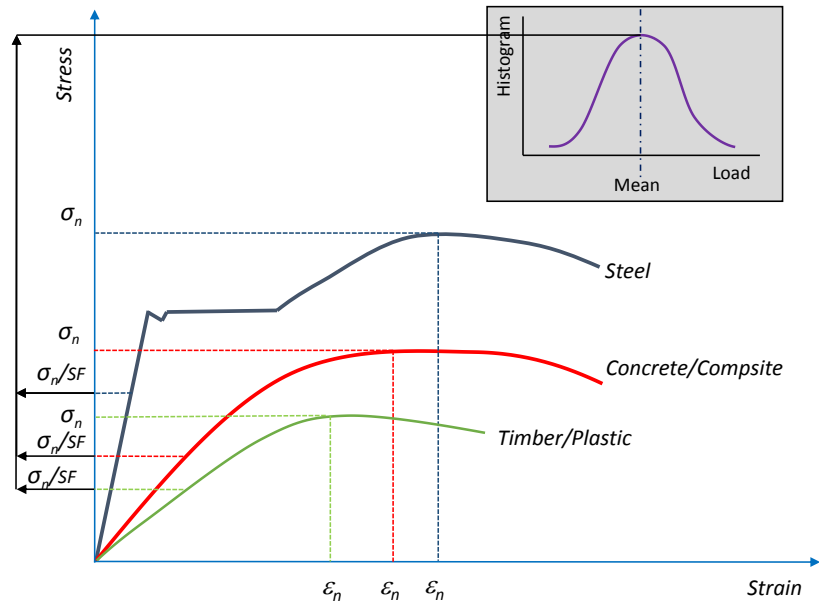


Figure 11. Allowable stress of materials (SF is safe factor)

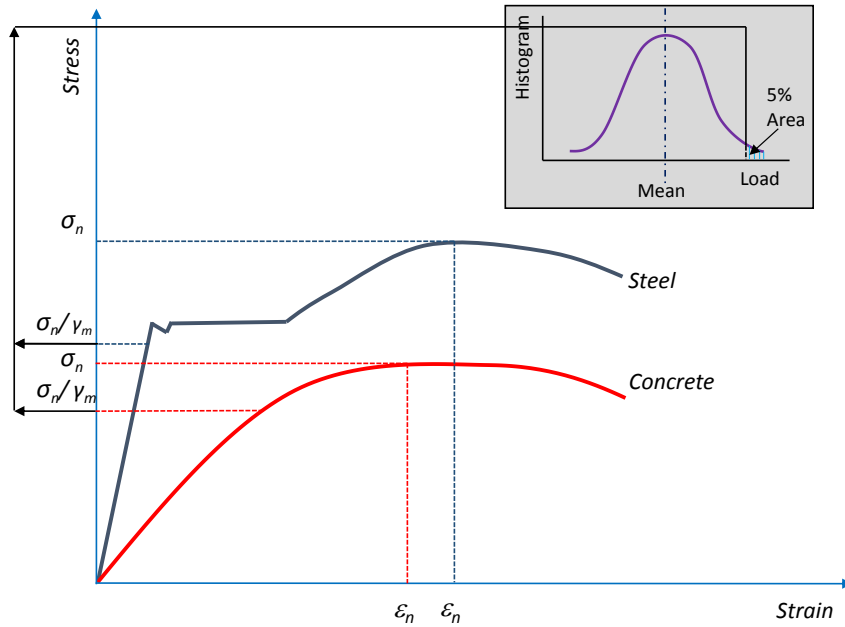


Figure 12. Ultimate limit states of materials (γ_m is material strength reduction factor)

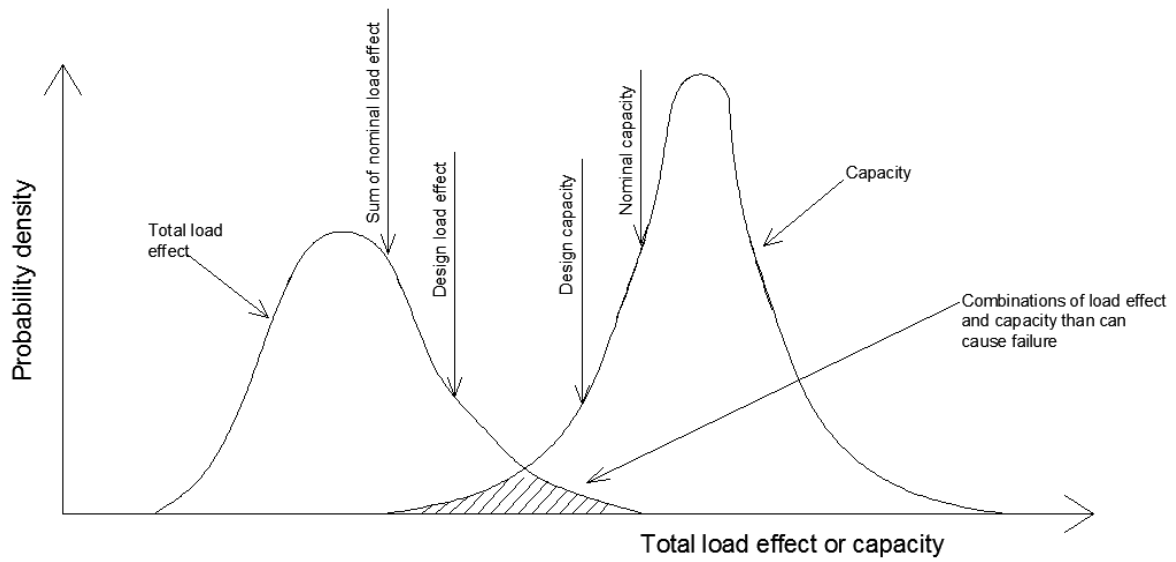


Figure 13. Model of probability density function

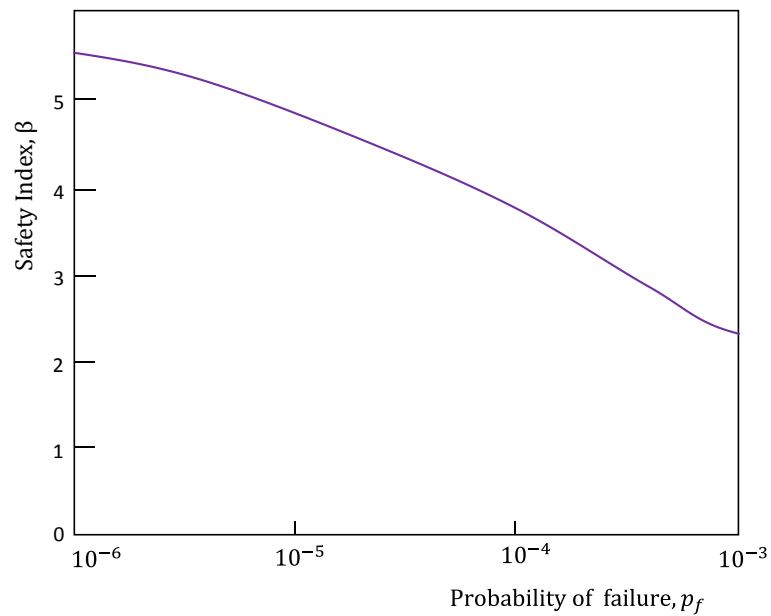


Figure 14. Graph: Safety Index (β) x Probability of failure (p_f) (AS5104 2005)



Figure 15. Hybrid polymer transoms (Van, Mckay 2013)